Gravity Wave Characteristics in the Southern Hemisphere Revealed by a High-Resolution Middle-Atmosphere General Circulation Model

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ABSTRACT

Gravity wave characteristics in the middle- to high-latitude Southern Hemisphere are analyzed using simulation data over 3 yr from a high-resolution middle-atmosphere general circulation model without using any gravity wave parameterizations. Gravity waves have large amplitudes in winter and are mainly distributed in the region surrounding the polar vortex in the middle and upper stratosphere, while the gravity wave energy is generally weak in summer. The wave energy distribution in winter is not zonally uniform, but it is large leeward of the southern Andes and Antarctic Peninsula. Linear theory in the three-dimensional framework indicates that orographic gravity waves are advected leeward significantly by the mean wind component perpendicular to the wavenumber vector. Results of ray-tracing and cross-correlation analyses are consistent with this theoretical expectation. The leeward energy propagation extends to several thousand kilometers, which explains part of the gravity wave distribution around the polar vortex in winter. This result indicates that orographic gravity waves can affect the mean winds at horizontal locations that are far distant from the source mountains. Another interesting feature is a significant downward energy flux in winter, which is observed in the lower stratosphere to the south of the southern Andes. The frequency of the downward energy flux is positively correlated with the gravity wave energy over the southern Andes. Partial reflection from a rapid increase in static stability around 10 hPa and/or gravity wave generation through nonlinear processes are possible mechanisms to explain the downward energy flux.

1. Introduction

Gravity waves are an essential component of the earth’s climate because of their ability to transport momentum mainly upward from the lower atmosphere (e.g., Fritts and Alexander 2003). The momentum deposition is important for maintaining weak wind layers in the lower stratosphere and in the upper mesosphere, and for simultaneously driving meridional circulations. Recent research on climate projection using chemistry–climate models suggests that the trend in upwelling in the tropical lower stratosphere can be largely affected by the location of the gravity wave drag through the downward control mechanism (e.g., McLandress and Shepherd 2009; Okamoto et al. 2011).

Another important role of gravity waves in the earth’s climate is to modify thermal structures in various ways in cooperation with planetary waves. Adiabatic heating associated with the vertical motion as a branch of the global-scale meridional circulation driven by the wave drag keeps the thermal structure much different from that expected by radiation: the summer polar upper mesosphere is the coldest place in the earth’s atmosphere because of the upward motion, leading to the formation of polar mesospheric clouds. The polar stratospheric clouds that appear in the polar winter are confined to the cold lower stratosphere because the middle and upper stratosphere in winter is warm owing to the downward motion. Gravity waves are primary waves that drive the meridional circulation in the summer and winter
mesosphere, while planetary waves are most important in the winter stratosphere (Plumb 2002). Gravity waves are also important for the formation of the easterly jet in the middle atmosphere in summer and hence the meridional circulation in this season (Alexander and Rosenlof 1996; Okamoto et al. 2011). Reversible temperature fluctuations associated with gravity waves are also important. In particular, when the temperature of the large-scale fields is marginal for the formation of polar mesospheric and stratospheric clouds, the gravity waves can modify the amount of these clouds (Eckermann and Preusse 1999; Carslaw et al. 1999; Wu and Jiang 2002; Hitchman et al. 2003; Shibata et al. 2003; Watanabe et al. 2006; McDonald et al. 2009; Kohma and Sato 2011).

With the aid of recent high-resolution satellite observations, our knowledge about gravity wave characteristics has been greatly improved particularly in the regions where ground-based observations are relatively sparse. The high-latitude Southern Hemisphere (SH) is one of such regions. Several studies have indicated that high mountains in the southern Andes and Antarctic Peninsula are strong sources of gravity waves and have examined the wave characteristics (e.g., Wu and Waters 1996; McLandress et al. 2000; Wu and Jiang 2002 [Microwave Limb Sounder (MLS)]; Eckermann and Preusse 1999; Preusse et al. 2002; Enn et al. 2006 [Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA)]; Jiang et al. 2002 [Upper Atmosphere Research Satellite (UARS) MLS]; Wu 2004 [the National Oceanic and Atmospheric Administration (NOAA) Advanced Microwave Sounding Unit-A (AMSU-A)]; de la Torre and Alexander 2005; Hei et al. 2008 (GPS radio occultation); Alexander and Teitelbaum 2007; Alexander and Barnett 2007 [Aqua/Atmospheric Infrared Sounder (AIRS)]). An interesting feature is that the wave energy is distributed far leeward from the mountains (McLandress et al. 2000; Wu 2004; Enn et al. 2006). Possible causes of the leeward propagation were discussed by Preusse et al. (2002) using a ray-tracing model.

Regarding the gravity wave sources in the Antarctic, Pfenninger et al. (1999) and Yoshiki and Sato (2000) analyzed gravity waves using operational radiosonde observation data at the South Pole and coastal Antarctic stations, respectively. A clear enhancement of gravity wave energy was commonly observed in spring in the height region of 15–25 km and in winter above about 25 km in the lower stratosphere. This spring enhancement was not observed in the Arctic stations (Yoshiki and Sato 2000). A similar spring maximum in the Antarctic was also reported using GPS occultation measurements (de la Torre et al. 2006; Baumgaertner and McDonald 2007). Horizontal distribution of gravity wave energy in the Antarctic was examined through satellite observations by Wu and Jiang (2002) by using MLS data and Baumgaertner and McDonald (2007) by using GPS occultation data. They showed the dominance of gravity waves along the coast of the Antarctic where the polar night jet is located in the winter stratosphere, as well as around the Antarctic Peninsula.

Several studies have focused on flow imbalance around the polar night jet as gravity wave sources in the polar region. By analyzing vertical energy propagation of gravity waves observed by operational and campaign observations using radiosondes, Yoshiki and Sato (2000), Yoshiki et al. (2004), and Sato and Yoshiki (2008) suggested that gravity wave sources are present in the stratosphere in the polar region and that a possible generation mechanism is a spontaneous adjustment of flow imbalance (McIntyre 2009) around the polar night jet. Hei et al. (2008) also examined gravity wave climatologies in the Antarctic and the Arctic using GPS occultation data. They primarily attributed the seasonal maximum of gravity wave energy to the generation of gravity waves through the geostrophic adjustment mechanism in the stratosphere. They claimed that the dominance of gravity waves over the Scandinavian Peninsula as shown by Yoshiki and Sato (2000) using radiosonde data was not seen in the GPS observations. However, we must be aware of the observational filter problem for the interpretation (Alexander 1998). Limb-view satellite observations such as the GPS occultation have a relatively low horizontal resolution (about a few hundred kilometers along a path for the case of GPS observation), although radiosondes make in situ observations—that is, they have a quite high horizontal resolution (not horizontal spacing). This low horizontal resolution of the GPS observation can cause significant underestimation of the amplitudes of gravity waves with small horizontal wavelengths, such as orographic gravity waves.

On the other hand, with the aid of recently developed supercomputer technology, gravity wave–resolving high-resolution climate models are available [see Watanabe et al. (2008) and references therein], although most climate models include gravity wave effects by using parameterizations because gravity waves are usually subgrid-scale phenomena (Alexander et al. 2010). Watanabe et al. (2008) developed a T213L256 middle-atmosphere general circulation model (GCM) and succeeded in simulating realistic zonal-mean zonal wind and temperature fields in the troposphere, stratosphere, and mesosphere without including any gravity wave parameterizations. It is likely that gravity waves with scales comparable to or smaller than the model resolution are not properly simulated (e.g., Preusse et al. 2002). However, several previous studies indicate that although the wavelengths of simulated gravity waves are largely affected by the
model resolution, the location of gravity wave generation is robust even in low-resolution models (O’Sullivan and Dunkerton 1995; Plougonven and Snyder 2005). The realistic dynamical and thermal structures of simulated fields by Watanabe et al. suggest that the momentum balance, including momentum transport by gravity waves, can be similar to that in the real atmosphere. In fact, seasonal variations of the momentum fluxes associated with gravity waves in the same model were consistent with the observations by mesosphere–stratosphere–troposphere (MST) radars in the stratosphere and mesosphere (Sato et al. 2009). In the present study, the characteristics of the gravity waves in high latitudes of the Southern Hemisphere are examined using high-resolution GCM simulation data by Watanabe et al. (2008). In particular, the geographical distribution and seasonal variation of energy and momentum fluxes of the gravity waves are shown. In this paper, we also focus on significant leeward and latitudinal propagation of orographic gravity waves, which likely provides significant gravity wave drag in the region far from the source mountains. The presence of downward-propagating gravity waves in the stratosphere is also shown and discussed in relation to the strong orographic gravity waves that radiate from the southern Andes.

A brief description of the model data used in this study is provided in section 2. The horizontal distribution of gravity wave energy, momentum fluxes, and intermittency is shown as a function of month and altitude in section 3. Horizontal propagation of gravity waves excited by high mountains in the southern Andes and Antarctic Peninsula is examined and discussed in section 4. The dominance of the downward energy propagation to the south of the Andes in the stratosphere is examined in section 5. A summary and concluding remarks are given in section 6.

2. Description of the gravity wave–resolving general circulation model

The T213L256 middle-atmosphere GCM developed by Watanabe et al. (2008) covers a height region up to 85 km in the upper mesosphere, with a horizontal resolution of about 60 km and vertical grid spacing of about 300 m above a height of 10 km. Such a high vertical resolution has not been used in middle-atmosphere GCMs in previous studies primarily because of limited computer resources. However, it may be necessary for obtaining realistic simulations of gravity wave propagation and dissipation. No gravity wave parameterizations were included in this model. Thus all gravity waves were spontaneously generated. However, the characteristics of simulated gravity waves also depend on artificial diffusion and cumulus parameterizations. A set of tuning parameters of the diffusion and cumulus parameterizations was carefully chosen by conducting several sensitivity tests to obtain gravity wave amplitudes in the lower stratosphere that are comparable to radiosonde observations over the central Pacific in the latitudinal range of 28°N–48°S (Sato et al. 2003). Time integration of over three model years was conducted using the Earth Simulator, in which a climatology with a realistic seasonal variation was specified for the sea surface temperature and stratospheric ozone. All physical quantities were sampled at a short time interval of 1 h. The model succeeded in simulating mean zonal wind and temperature fields consistent with observations. Watanabe et al. (2008) illustrated an overview of the model performance including momentum budgets in the middle atmosphere.

A quasi-biennial oscillation (QBO)-like oscillation in the equatorial lower stratosphere was also spontaneously generated with realistic amplitudes in the model simulation, although the period (about 15 months) is shorter than the observed value (about 28 months). Kawatani et al. (2010a,b) analyzed the driving mechanism of the QBO-like oscillation by separating the various contributions from different types of waves. They showed that the momentum fluxes associated with simulated gravity waves in the equatorial region were consistent with or slightly larger than the estimates from radiosonde observations in Singapore by Sato and Dunkerton (1997). Considering the simulated disturbances as an effective surrogate of the real ones, Sato et al. (2009) examined the global distribution of gravity wave sources and their propagation in the meridional cross section of the middle atmosphere. They suggested that latitudinal propagation of gravity waves into the mesospheric jet was significant in both summer and winter, which may be important for the formation of the jet structure itself. These results from high-resolution GCMs are useful for providing constraints on uncertainty of the gravity wave parameterizations. These model data were also used to examine the fine structure of the tropopause and stratopause (Miyazaki et al. 2010a,b; Tomikawa et al. 2008), and 4-day wave dynamics in the mesosphere (Watanabe et al. 2009).

The present study concentrates on the characteristics of gravity waves and their three-dimensional propagation in high latitudes of the Southern Hemisphere. Similar to Sato et al. (2009), small horizontal-scale fluctuations with total wavenumber $n$ greater than 22 (horizontal wavelengths $\leq 1800$ km) are designated as gravity waves.

Figure 1 shows an example of the observed and simulated gravity wave structures at around 3 hPa ($\sim 40$ km) in the middle stratosphere. Figures 1a and 1b show the
radiance fluctuations around the southern Andes and Antarctic Peninsula observed by AIRS on 1 August and 10 September 2003, respectively (Alexander and Barnet 2007). Wavelike structures with phases aligned in the north–south direction are seen over the southern Andes in Fig. 1a. Bent phase structures are observed leeward of the southern Andes in Fig. 1b. Figure 1c shows simulated temperature fluctuations on 3 September in the first year with $n > 22$ and vertical wavelengths greater than 12 km, which correspond to the observational filter of AIRS. The characteristic wave structures observed in Figs. 1a and 1b are well simulated by the model. Typical horizontal wavelengths are about 300–400 km in both the observation and the simulation.

The typical horizontal wavelengths over the southern Andes and Antarctic Peninsula are consistent with previous studies using satellite observations. Eckermann and Preusse (1999) reported that gravity waves observed by CRISTA in early November 1994 had a horizontal wavelength of about 400 km over the southern Andes. Preusse et al. (2002) carefully analyzed gravity waves observed by CRISTA and simulated gravity waves using a mesoscale model for the same period as examined by Eckermann and Preusse (1999). Preusse et al. showed that the dominant horizontal wavelengths were about 400 km at the southern tip of South America. Jiang et al. (2002) examined gravity waves on the Andes observed by UARS MLS and estimated two preferential horizontal wavelengths at about 110 and 400 km. Alexander and Teitelbaum (2007) detected gravity waves over the Antarctic Peninsula with horizontal wavelengths of about 300 km from AIRS observation.

3. Climatology of gravity waves in the Southern Hemisphere

Gravity wave activity is largely affected by background dynamical fields. In our model, the zonal wind at 10 hPa changes from westerly to easterly in early December for the first and third years and in early November for the second year in the high latitudes of the Southern Hemisphere. The seasonal transition in early December accords with the observational climatology [e.g., Stratospheric Processes and Their Role in Climate (SPARC) climatology; see http://www.sparc.sunysb.edu/html/temp_wind.html]. Thus, we mainly analyzed data of the first model year to examine the gravity wave climatology.

Figure 2 shows polar-stereo projection maps of gravity wave potential energy \[ (\frac{g^2}{2N^2})\overline{\theta'^2} \] at 10 hPa in the Southern Hemisphere as a function of month, where $g$ is the gravitational acceleration, $N$ is the Brunt–Väisälä frequency, $\theta$ and $\theta'$ are the potential temperature and its fluctuations associated with gravity waves, respectively, and the overbar represents the time and/or spatial average. Thick contours show monthly mean zonal winds. The GWPE is large around the stratospheric polar night jet in winter in the middle to high latitudes, while the GWPE is small in summer. These characteristics are consistent with previous
observational studies using radiosonde and satellite data (Yoshiki and Sato 2000; Yoshiki et al. 2004; Wu 2004; Baumgaertner and McDonald 2007; Hei et al. 2008).

The GWPE distribution is not zonally uniform. Large GWPE values are observed over and leeward of the southern Andes and Antarctic Peninsula from June through September when the polar night jet is strong. This dominance of gravity waves over the southern Andes was reported by previous studies using high-resolution satellite observations (McLandress et al. 2000; Jiang et al. 2002; Wu and Jiang 2002; Ern et al. 2006), regardless of different observation methods (i.e., different observational filters). This fact means that gravity waves in this region are a mixture of fluctuations having various horizontal and vertical wavelengths. The strong GWPE around the southern Andes and Antarctic Peninsula is extended zonally over a longitudinal distance longer than 180°. For example, the region with a GWPE of 6 J kg⁻¹ extends to the date line in June and October, and to a longitude of about 120°W in July, August, and September.

In the two-dimensional framework, the horizontal group velocity of stationary hydrostatic gravity waves such as orographic gravity waves is almost zero. Thus, the distribution of gravity waves leeward of the mountains seems contradictory to the theoretical expectation. The possible horizontal propagation of gravity waves forced by the topography of the southern Andes was discussed by Preusse et al. (2002). We revisit the mechanism in detail in the next section.

In addition to the zonally elongated gravity wave distribution, there are a few spotty areas with large GWPE on the coast of the Antarctic Continent such as around 20°–30°E and near the Ross Sea in July. Owing to the presence of steep slopes in these regions, these spotty

Fig. 2. Polar stereo projection maps of gravity wave potential energy (shading) in the SH for each month at 10 hPa. Monthly mean zonal winds are shown by thick contours at an interval of 40 m s⁻¹.
areas probably occur because of generation of gravity waves in association with strong surface winds such as katabatic winds (Watanabe et al. 2006). Similar features are observed in the GWPE distribution in the second and third model years (not shown).

Figures 3a and 3b show polar-stereo projection maps at 100, 10, and 1 hPa of the monthly mean vertical fluxes of zonal $r_0u'w'$ and meridional momentum $r_0v'w'$, respectively. Here $r_0$ is the basic atmospheric density, and $u'$, $v'$, and $w'$ are zonal, meridional, and vertical wind fluctuations, respectively. According to a linear theory, the direction of the horizontal momentum flux vector $(r_0u'w', r_0v'w')$ is the same as that of the wavenumber vector for gravity waves if they propagate energy upward.

At 100 hPa in the lower stratosphere, $r_0u'w'$ is negative in most regions. In particular, it is dominant in regions with high mountains such as over the Andes, East Africa, eastern Australia, and the Antarctic Peninsula. The zonal winds are westerly in most regions displayed in Fig. 3a at this level. Thus, this feature is consistent with orographic gravity waves that propagate upward in westerly winds.
At upper levels (10 and 1 hPa), negative $\rho_0 \bar{u}' \bar{w}'$ values are observed only in the higher-latitude regions. The magnitude of negative $\rho_0 \bar{u}' \bar{w}'$ at the upper levels is maximized along the polar night jet. The boundary of the negative $\rho_0 \bar{u}' \bar{w}'$ region is located slightly poleward of zero zonal wind contours. The dominance of negative $\rho_0 \bar{u}' \bar{w}'$ in the Andes in the lower latitudes, East Africa, and eastern Australia is not clear at this level, which is consistent with the critical level filtering of topographically forced gravity waves. Instead, $\rho_0 \bar{u}' \bar{w}'$ is positive in the lower-latitude region where the mean wind is easterly. This fact suggests that gravity waves tend to have an intrinsic phase velocity opposite to the mean winds.

Unlike $\rho_0 \bar{u}' \bar{w}'$, $\rho_0 \bar{v}' \bar{w}'$ have both positive and negative values. At 100 hPa, it is mainly negative to the south and leeward of the Andes, while positive values are dominant around 30°S at the same longitudes. A similar feature (i.e., negative values at lower latitudes and positive values at higher latitudes) is observed over East Africa and eastern Australia. These common characteristics of $\rho_0 \bar{v}' \bar{w}'$ suggest that topographically forced gravity waves propagate outward meridionally from the mountainous regions, although the sign of $\rho_0 \bar{v}' \bar{w}'$ should primarily depend on the alignment of respective mountain ridges relative to the mean wind.

The distribution is simpler at the upper levels (1 and 10 hPa). Negative $\rho_0 \bar{v}' \bar{w}'$ are dominant in the low-latitude side of the polar night jet, while weak positive $\rho_0 \bar{v}' \bar{w}'$ values are observed on the high-latitude side. Positive $\rho_0 \bar{v}' \bar{w}'$ is particularly dominant over the Antarctic Peninsula. These characteristics of $\rho_0 \bar{v}' \bar{w}'$ suggest that the gravity waves are focused into the polar night jet. An explanation of the latitudinal focusing of gravity waves is given by Dunkerton (1984), Eckermann (1992), and Sato et al. (2009) by considering that the wavenumbers have both positive and negative values. At 100 hPa, intermittency is high in the mountainous regions where large GWPE is observed. This result is consistent with that of Hertzog et al. (2008) based on quasi-Lagrangian observations using super-pressure balloons (the Vorcore campaign) in Antarctica. At 10 and 1 hPa, high intermittency is also observed in the region with large GWPE leeward of the Andes and Antarctic Peninsula. This feature is also consistent with the inference that the orographic gravity waves propagate energy leeward.

4. Horizontal propagation of orographic gravity waves

The leeward propagation of orographic gravity waves is discussed in the three-dimensional framework in this section. Preusse et al. (2002) indicated this possibility by referring to the theoretical study by Smith (1980) that showed gravity wave generation and propagation over an isolated mountain in the three-dimensional space. The leeward propagation of orographic gravity waves is important for global circulation because such gravity waves may deposit their momentum over the oceans, far from their source. Thus, it is of value to discuss this issue again by using a few illustrative figures for this particular case observed leeward of the Andes and Antarctic Peninsula, although the essence is inherently expressed in the equations derived by Smith (1980).

Figure 4 shows snapshots of the horizontal wind divergence simulated by the model in various cross sections at 1300 UTC 5 August in the second year. The displayed divergence is unfiltered, namely, an original field. Gravity wave packets are observed over the southern Andes in the latitudes 30°–55°S. The horizontal wavelengths are estimated at about 300 km from Figs. 4a and 4b, which roughly accord with the estimates in previous studies using satellite observation data as described in section 2. The phase alignments from the northwest to southeast indicate that the wavenumber vectors point to the southwest. The direction of the wavenumber vectors is more southward at 10 hPa than at 100 hPa.

The phases of the gravity waves in the longitude–height section at 50°S (Fig. 4c) are slanted to the west with height, which is consistent with orographic gravity waves in the westerly (eastward) winds. The wave packet is mainly concentrated around the Andes in the zonal direction. On the other hand, in the latitude–height section (Fig. 4d), the region with large wave energy and gravity wave phases are slanted upward and southward. This feature suggests that the gravity waves have a non-zero horizontal group velocity and propagate upward and southward. Note that a nondimensional factor proportional to $\exp(-z/H)$, where $z$ is the altitude and $H$ is the scale height (about 7 km), was multiplied with the horizontal divergence in Figs. 4c and 4d so as to see the phase structure clearly in these vertical sections, and hence the vertical variation of the amplitudes does not have meaning.

Regarding the strong gravity waves frequently observed over the Antarctic Peninsula (Fig. 2), typical horizontal wavelengths are about 300 km and the wave-number direction is mainly northwestward (not shown in detail, but seen in Fig. 1, for example).
FIG. 4. Snapshots of horizontal wind divergence at 1300 UTC 5 August in the second year. Maps at (a) 100 and (b) 10 hPa. (c) Longitude–pressure and (d) latitude–pressure sections. A factor depending on \( z \), \( \exp(-z/4H) \), is multiplied to see the vertical phase structure clearly. Contours of \( \pm 1 \times 10^{-4}, \pm 3 \times 10^{-4} \), and \( \pm 5 \times 10^{-4} \) s\(^{-1}\) are drawn. Regions with values larger (smaller) than \( 1 \times 10^{-4} \) (\( 1 \times 10^{-4} \)) s\(^{-1}\) are darkly (lightly) shaded.
a. Ray-tracing analysis

We conducted a ray-tracing analysis in order to examine the leeward propagation of the orographic gravity waves, by taking a horizontal wavelength of 300 km and southwestward and northwestward wavenumber vector directions over the Andes and the Antarctic Peninsula, respectively, as typical parameters. Ground-based phase speeds are set to zero. Results of the ray-tracing analysis are shown in Fig. 5. In this calculation, an idealized background wind field is assumed as shown by the contours in Fig. 5a. The background wind field mimics the simulated field but is assumed to be strong in a broad latitude region in the lower troposphere so that the gravity waves can propagate upward both in the southern Andes and Antarctic Peninsula, although it is not always the case as will be shown later. Launch latitudes are denoted by two thick horizontal bars on the bottom axis of Fig. 5a, which correspond to the locations of the South American continent and the Antarctic Peninsula, respectively. A launch longitude is taken to be 70°W (Fig. 5b).

The gravity wave packets starting from the latitudes to the north of 45°S do not propagate upward because the mean wind is so weak that the intrinsic frequency becomes smaller than the inertial frequency (Jones’ critical level; Jones 1967). As seen in the latitude–height section of Fig. 5a, the rays are focused into the polar night jet, which is consistent with the mechanism discussed by Dunkerton (1984), Eckermann (1992), and Sato et al. (2009). Figure 5b shows the rays in the longitude–latitude section. Open (closed) circles indicate heights of the rays every 20 km for the wave packets originally having southwestward (northwestward) wavenumber vectors. It is important that the wave packets propagate significantly eastward. The longest ray is located at a longitude distance of 60° from its origin at an altitude of 60 km.

The mechanism of leeward propagation of stationary gravity waves is illustrated by Fig. 6. Here we assume that the wavenumber vector \( \mathbf{k} \) points to the southwest and that the mean wind \( \mathbf{U} \) is westerly (eastward) for simplicity. The intrinsic horizontal group velocity \( \mathbf{c}_g \) is parallel to the horizontal wavenumber vector and is balanced with the mean wind component parallel to the wavenumber vector \( \mathbf{U}_k \). Thus, the wave packet does not propagate in the direction of its horizontal wavenumber vector. This feature is consistent with the linear theory in the two-dimensional framework. However, the wave packet is advected freely by the mean wind component perpendicular to the wavenumber vector \( \mathbf{U}_\perp \). Note that \( \mathbf{U}_\perp \) is identical to the ground-based horizontal group velocity \( \mathbf{c}_g \), which is a vector sum of \( \mathbf{c}_g \) and the mean wind \( \mathbf{U} \). In conclusion, stationary gravity waves, such as orographic gravity waves, can significantly propagate energy leeward if their wavenumber vectors are not parallel to the mean wind. The GWPE distribution in Fig. 2, which extends leeward from the Andes and the Antarctic Peninsula focusing into the latitude in between, is understood by this mechanism.

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**Fig. 5.** Projections of rays of orographic gravity waves (thick curves) in (a) the latitude–height and (b) the longitude–latitude sections. The initial horizontal wavelengths are 300 km, and the initial wavenumber vectors point to the southwest (northwest) at latitudes lower (higher) than 60°S. Contours in (a) show an idealized background zonal wind field used for the ray-tracing calculation. Thick horizontal bars at the bottom of (a) indicate the latitudes of the South American continent and the Antarctic Peninsula. Circles on the rays in (b) show locations at altitudes of 0, 20, 40, and 60 km.
An interesting result is that gravity waves hardly propagate upward for the wavelength of 400 km (thus, not shown). The mean wind in which orographic gravity waves can propagate upward has an upper limit $U_{\text{min}}$ because of Jones’ critical level:

$$ U_{\text{min}} = f/k, $$

where $f$ is the inertial frequency. This equation indicates that $U_{\text{min}}$ is larger for smaller $k$. This implies that gravity waves with extremely long horizontal wavelengths hardly propagate upward. This characteristic constrains the leeward distance that gravity waves can reach.

It is also worth noting that the rays shown in Figs. 7 and 8 tilt largely and hence gravity waves propagate more leeward in the lower stratosphere, compared with those in the middle and upper stratosphere. This is primarily because the vertical group velocities are smaller in weaker mean winds in the lower stratosphere. This feature seems consistent with the characteristic of the gravity wave distribution that is confined near the Andean region at 100 hPa and similarly spread leeward at 10 and 1 hPa.

### Correlation analysis

A correlation analysis was made to confirm this leeward propagation. First, we constructed a data series of daily-averaged GWPE from June through October of the three model years at each grid. Next, the Andean GWPE data series was constructed by averaging grids around the Andes as shown by the thick rectangle in Fig. 9. Then, the correlation was calculated for the data series of the Andean GWPE and the GWPE at each grid. The results are shown by contours in Fig. 9 for 100, 10, and 1 hPa (about 16, 32, and 48 km, respectively). Correlations greater than 0.132 are meaningful with a 90% statistical significance.

Positive correlation is observed more leeward at higher altitudes. The area with significant correlation is similar to the gravity wave distribution (see Figs. 3 and 4a). This fact supports the inference from the ray-tracing analysis that the energy of gravity waves generated over the Andes is advected far leeward by the mean wind during their upward propagation. This means that orographic gravity waves can deposit their momentum in a horizontal region that is far distant from their origin.

Another interesting feature in Fig. 9 is a statistically meaningful positive correlation observed even windward of the southern Andes at 10 and 1 hPa. This feature cannot be explained by simple advection of stationary gravity waves by the mean wind. There are at least
three possible explanations. One is that the gravity waves may not be “stationary” because they are usually generated in time-varying background winds (e.g., Sato 1990). Such gravity waves have nonzero phase velocities and some of them can propagate windward. Another possible explanation is a nonlinear effect. Using a two-dimensional full nonlinear anelastic numerical model, Bacmeister and Schoeberl (1989) showed that secondary gravity waves generated in the breaking region of the primary orographic gravity waves in the stratosphere have nonzero phase velocities, which allows some of them to propagate windward. The third possible explanation is the coexistence of gravity waves generated by different mechanisms. It is possible that strong surface winds generating orographic gravity waves are sometimes associated with the passage of a frontal system. Such a frontal system can radiate gravity waves having nonzero phase velocities through spontaneous adjustment mechanisms (Plougonven and Snyder 2005; Zhang 2004).

It is also interesting that a negative correlation is observed around 65°S near the Antarctic Peninsula in Fig. 9, although the statistical significance is marginal. This negative correlation indicates a seesaw-like occurrence of gravity waves over the Andes and the Antarctic Peninsula. This feature probably reflects the latitudinal movement of the polar-front jet causing orographic gravity waves.

The correlation analysis was also made by considering a time lag. However, the correlation coefficient did not increase. This is likely because the upward group velocity...
of gravity waves is sufficiently high. For example, the shortest ray from 55°S takes only 12 h and the longest ray from 46°S takes 52 h to reach the 1-hPa level in Fig. 5.

It is also worth noting that the zonally elongated region with a strong gravity wave activity in winter (Figs. 2 and 3) cannot be fully explained by the leeward propagation of gravity waves from the Andes and the Antarctic Peninsula particularly for the region to the far east of the date line. It is likely that the rest of the strong GWPE region is attributable to gravity waves generated by other mechanisms. Spontaneous adjustment of imbalance around the polar night jet (Sato and Yoshiki 2008) and jet–front systems (Shibata et al. 2003; Zhang 2004; Plougonven and Snyder 2007) as well as generation from strong katabatic winds in the Antarctic (Watanabe et al. 2006) are possible candidates.

Fig. 8. As in Fig. 7, but for initial horizontal wavelengths of 250 and 350 km. Initial wavenumber vectors point in the direction of 240°. Note that no rays propagate upward for the wavelength of 400 km (not shown).

Fig. 9. Maps of correlation between the daily time series of gravity wave potential energy at each location and that averaged for the thick rectangular region from June through October at (a) 100, (b) 10, and (c) 1 hPa. The regions with correlation greater than 0.132 and smaller than −0.132 are darkly and lightly shaded, respectively. A correlation greater than 0.132 is statistically significant.
5. Existence of gravity waves propagating energy downward

It is believed that most sources of gravity waves are present in the troposphere, and hence gravity waves propagate energy mainly upward in the stratosphere and above. However, previous studies based on radiosonde observations (e.g., Sato and Yoshiki 2008) reported that a significant percentage of gravity waves propagate energy downward in the Antarctic stratosphere. Sato and Yoshiki (2008) observed a high correlation between the gravity wave energy and the stratospheric background wind. They concluded that the downward propagation is likely due to the wave generation through spontaneous adjustment processes around the polar night jet in the stratosphere. Sato and Yoshiki (2008) observed a high correlation between the gravity wave energy and the stratospheric background wind. In addition, gravity waves propagated upward and downward from a pressure level in the stratosphere where the mean wind field showed significant departure from the geostrophic balance. They concluded that the downward propagation is likely due to the wave generation through spontaneous adjustment processes around the polar night jet in the stratosphere. The generation of gravity waves in the stratosphere around the polar night jet was also reported and the importance of these gravity waves for the momentum budget of a sudden stratospheric warming event in the Northern Hemisphere was discussed by Yamashita et al. (2010).

In our model, downward-propagating gravity waves are primarily observed to the south of the region where gravity waves from the southern Andes are dominant. We examined the possibility of the spontaneous generation of gravity waves by analyzing the distribution of the residual of a nonlinear balance equation \( \delta \text{NBE} \) (e.g., Zhang 2004), a parameter that describes flow imbalance. However, significant values of \( \delta \text{NBE} \) were not observed around the location where the downward energy flux originated (not shown). Thus we need to consider other mechanisms to explain the downward energy propagation.

a. Climatologies of downward energy propagating gravity waves

Figure 10 shows a polar projection map of the GWPE (contours) and percentage of cases having a downward energy flux (shadings) from July through September for 3 yr. The vertical energy flux is defined as \( \rho_0 z' w' \), where \( z' \) is the geopotential height component of the gravity waves. High frequency of the downward energy flux is observed to the south of the region where orographic gravity waves from the southern Andes are dominant by 10\(^\circ\)–15\(^\circ\). The western edge of the high-frequency region is located to the east of the dominant GWPE region by 10\(^\circ\). It is important to note that the GWPE is also large in the region of 30\(^\circ\)–90\(^\circ\)E, but downward energy flux is not frequent to the south of this region. This fact suggests that the downward energy propagation is closely related to the orographic gravity waves from the southern Andes.

Next we examined the temporal variation of GWPE averaged for 75\(^\circ\)–25\(^\circ\)W and 38\(^\circ\)–48\(^\circ\)S, and the frequency of downward energy flux averaged for 65\(^\circ\)–15\(^\circ\)W and 50\(^\circ\)–60\(^\circ\)S as a function of height (Figs. 11a,b), respectively. Six-day mean values are analyzed. The GWPE in Fig. 11a is multiplied by a factor \( \exp (-z/2H) \) so as to see the time variation clearly. Both the GWPE and frequency of the downward energy flux are large in the stratosphere from May through October when the strong polar night jet is present. The downward energy flux is less frequent in the upper stratosphere. Figure 11c shows a scatter diagram of the GWPE and frequency of the downward energy flux from May through October. A positive correlation is observed between the two quantities, supporting the inference of a close relationship between the downward energy flux and orographic gravity waves from the southern Andes.

b. Case study for 25–30 August in the second year

An analysis was made for the time period of 25–30 August in the second year at 30 hPa when downward energy propagation was clearly observed. Figure 12 shows a horizontal map of the GWPE by shadings and mean zonal winds by thin contours. Thick curves indicate the...
region where the vertical energy flux is downward. The gravity waves originating from the Andes are dominant around a latitude of 40°S. The downward energy flux is observed to the south of this region.

The latitude–height section of the GWPE (shading) and the energy flux vector \(\mathbf{u} = (u, v, w)\) (arrows) at 55°W is shown in Fig. 13. Contours show the mean zonal winds. The upward and southward energy flux is dominant in latitudes from 35°S (100 hPa) to the core of the westerly jet around 50°S (1 hPa), while the downward and southward energy flux is observed around a latitude of 50°S below 10 hPa, which is to the south of the region where the upward energy flux is dominant at the same altitudes.

Figure 14 shows a snapshot of the latitude–height section of the horizontal wind divergence. Phase alignments are southward and upward to the north of 50°S and southward and downward to the south. These phase structures are consistent with the characteristics of energy fluxes in Fig. 13: respective gravity waves propagate energy upward and downward in the vertical and southward in the latitudinal. The wavelengths of the upward and downward propagating gravity waves are similar, suggesting a reflection around 10 hPa.

c. Possible mechanisms of downward wave propagation

In the primitive equation system assuming hydrostatic balance as in our GCM, full reflection does not occur as explained below. The linear theory indicates that the dispersion relation for nonhydrostatic gravity waves is

\[
\omega^2 = \frac{f^2 m^2 + N^2 k^2}{k^2 + m^2},
\]

where \(\omega\) is the intrinsic frequency, \(k\) is the horizontal wavenumber, and \(m\) is the vertical wavenumber. Using this equation, the vertical group velocity is expressed as

\[
c_{gz} = \frac{\partial \omega}{\partial m} = -\frac{mk^2(N^2 - f^2)}{\sqrt{(f^2m^2 + N^2 k^2)(k^2 + m^2)^3}}.
\]

Thus, \(c_{gz} \to 0\) when \(m \to 0\), and hence, full reflection occurs for the gravity waves at this limit. On the other hand, the dispersion relation for hydrostatic gravity waves is

\[
\omega^2 = f^2 + \frac{k^2}{m^2}N^2,
\]
and the vertical group velocity is expressed as

\[ c_{gz} = -\frac{mk^2 \text{N}^2}{\sqrt{(f^2 m^2 + \text{N}^2 k^2)m^2}}. \] (5)

Thus, for the hydrostatic equation system, \( c_{gz} \to \infty \) when \( m \to 0 \) and hence full reflection does not occur at this limit. However, even in the primitive equation system, partial reflection can occur if the vertical gradient of static stability \( \text{N}^2 \) is large.

Figure 15 shows vertical profiles of the temperature and the Brunt–Väisälä frequency squared \( \text{N}^2 \) at 50°S and the latitude–height section of \( \text{N}^2 \) around 55°W at the end of August. The tropopause and stratopause are located at 250 and 0.7 hPa, respectively. The vertical gradient of temperature varies significantly at 10–20 hPa in the middle stratosphere. The values of \( \text{N}^2 \) are about \( 3.8 \times 10^{-4} \) and \( 5.2 \times 10^{-4} \) s\(^{-2}\) below and above the transition level, respectively. The transition is rapid compared with the vertical wavelength of the gravity waves as observed in Fig. 14. Thick closed curves show the region in which the downward energy propagation is dominant. The top of this region roughly corresponds to the transition level of \( \text{N}^2 \). Note that such a discrete transition of \( \text{N}^2 \) in the middle stratosphere is uniquely observed in high-latitude regions in winter, because solar radiation that should be absorbed by the ozone layer is quite weak or zero.

To understand the partial reflection mechanism, we considered an idealized situation in which the background fields are constant except for discreteness in \( \text{N} \) (i.e., \( \text{N} = \text{N}_1 \) for \( z < 0 \) and \( \text{N} = \text{N}_2 \) for \( z > 0 \), where \( \text{N}_2 > \text{N}_1 \)). The equation for the vertical wind amplitude \( W \) of a monochromatic hydrostatic gravity wave is

\[ \frac{d^2W}{dz^2} + \frac{\text{N}^2 k^2}{\omega^2 - f^2} W = 0. \] (6)

Because of the assumption of horizontally uniform and steady background fields, \( k \) and \( \omega \) do not vary through the propagation. Thus, \( m^2 \) in (6) depends only on \( \text{N} \).

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**Fig. 12.** Horizontal map of gravity wave potential energy (shading) and mean zonal winds (thin contours; contour interval of 20 m s\(^{-1}\)) for the time period of 25–30 August in the second year at 30 hPa. Thick curves show the region where the net vertical energy flux is downward (i.e., contours of zero flux are shown).

**Fig. 13.** Latitude–height section of the gravity wave potential energy (shading) and energy flux vectors (arrows) for the time period of 25–30 August in the second year at 55°W. Contours show the mean westerly wind at an interval of 20 m s\(^{-1}\).

**Fig. 14.** Snapshot of the horizontal wind divergence in the latitude–height section at 55°W at 0300 UTC 29 August in the second year. Values are weighted by exp\((-z/4H)) to see the phase structure easily. Contour intervals are the same at each level. Positive regions are darkly shaded.
By solving (6), the partial reflection rate $R$ of the wind amplitude is obtained as

$$R = \frac{N_2 - N_1}{N_1 + N_2}. \tag{7}$$

By taking the values above and below the transition level of 10–20 hPa, $R$ is estimated at about 8%. This partial reflection rate is not sufficiently large to explain the simulated downward energy propagation of gravity waves. However, it is worth noting that the reflected waves are detectable even if the wave energy is weak. Because the latitudinal group velocity is southward, the reflected waves are located to the south of the incident waves and do not interfere with them, which is consistent with the relative location of the regions with a strong GWPE and a dominant downward energy flux.

Another possible mechanism is the nonlinear effect. Using a two-dimensional nonlinear model, Bacmeister and Schoeberl (1989) showed that downward propagating gravity waves are generated in the breaking region of the primary orographic gravity waves. The downward-propagating gravity waves significantly reduce the vertical momentum fluxes in the flow which extends far below the breaking level. The downward-propagating gravity waves have nonzero phase speeds, indicating that these waves are generated through nonlinear processes around the breaking region.

Such a nonlinear wave generation may have also occurred in our GCM simulation. The positive correlation between the GWPE and the frequency of the downward energy flux, as shown in Fig. 11c, is consistent with this inference. Note also that this nonlinear wave generation can explain windward distribution of gravity wave activity as discussed in section 4b. The background fields,

![Figure 15](http://journals.ametsoc.org/doi/pdf/10.1175/JAS-D-11-0101.1)
6. Summary and concluding remarks

Using data from a high-resolution middle-atmosphere general circulation model, which explicitly simulates gravity waves, a climatology of gravity waves was analyzed for middle and high latitudes of the Southern Hemisphere. Gravity waves in the stratosphere were mainly distributed surrounding the polar vortex in winter, while gravity wave energy was generally weak in summer. This feature is consistent with previous studies using satellite observations.

The wave energy was not uniformly distributed in the zonal direction, but it is significantly large leeward of the southern Andes and Antarctic Peninsula. It was theoretically illustrated that orographic gravity waves can significantly propagate leeward by the mean wind component perpendicular to the wavenumber vector. The results of ray-tracing and correlation analyses were consistent with this theoretical expectation. The longitudinal distance of the leeward energy propagation amounts to several thousand kilometers, which explains a significant part of the gravity wave band around the polar vortex in winter.

It was shown that the downward energy flux was dominant in the stratosphere to 10°–15° south of the region where strong gravity wave energy was observed. There was positive correlation between the gravity wave potential energy and frequency of the downward energy flux, indicating that the downward-propagating gravity waves are closely related to orographic gravity waves excited over the southern Andes. Possible mechanisms for the existence of gravity waves propagating energy downward are partial reflection from a rapid increase in static stability around 10 hPa and/or generation of gravity waves through nonlinear processes in association with primary orographic waves that have large amplitudes.

A transition layer of static stability in the middle stratosphere is unique but common in the winter polar region, which is related to the warm temperature maintained by adiabatic heating associated with the downward branch of the meridional circulation driven by atmospheric waves. Thus, the tropopause in the winter polar region is sometimes incorrectly estimated at a height in the lower stratosphere (e.g., around 25 km) following the definition by the World Meteorological Organization based on the vertical gradient of temperature.

It is also worth noting that similar partial reflection of gravity waves may be important at the tropopause and mesopause, where the vertical gradient of static stability is quite large. If we consider a typical ratio of $N$ in the stratosphere to that in the troposphere is about 2, (7) indicates that about 30% of gravity waves are reflected at the tropopause. In the real atmosphere, the tropopause structure in the middle latitudes is so fine that the vertical gradient of $N$ is quite large (Gettelman et al. 2011), suggesting significant partial reflection around the tropopause.

The gravity wave characteristics shown by the present study, such as the horizontal propagation of orographic gravity waves, partial reflection in the flow, and secondary generation of gravity waves in the flow are not included in the gravity wave parameterizations used in most global models. The results of this study indicate that the mountain wave drag can be present even over the oceans and/or land regions without high mountains through the horizontal propagation of gravity waves generated over the high mountains.

Sources of the gravity waves that are dominant far east of the date line in the high latitudes of the Southern Hemisphere are one of the remaining issues to be examined in the future. Katabatic winds over steep slopes of the Antarctic continent, jet–front systems in the troposphere, and in situ generation in the stratosphere by the spontaneous adjustment around the polar night jet are possible candidates.

A difference between the real and our model atmospheres is that downward energy propagation is more frequent in the real high-latitude stratosphere (e.g., Yoshiki and Sato 2000). This point should also be explored in the future.

The high-resolution model is quite useful for quantitatively examining the role of gravity waves in the global atmosphere, because observational data have various limitations for quantitative discussion on the momentum balance. A combination of high-resolution global models, high-resolution satellite and ground-based observations such as MST radars (Sato et al. 2011) will be powerful and useful approaches for thorough understanding of the gravity wave characteristics and their role in the real atmosphere.

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